

Systems Engineering Approach to Technology Integration for NASA's 2nd Generation Reusable Launch Vehicle

By

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ABSTRACT

The overall goal of the 2nd Generation RLV Program is to substantially reduce technical and business risks associated with developing a new class of reusable launch vehicles. NASA's specific goals are to improve the safety of a 2nd-generation system by 2 orders of magnitude — equivalent to a crew risk of 1-in-10,000 missions — and decrease the cost tenfold, to approximately \$1,000 per pound of payload launched.

Architecture definition is being conducted in parallel with the maturing of key technologies specifically identified to improve safety and reliability, while reducing operational costs. An architecture broadly includes an Earth-to-orbit reusable launch vehicle, on-orbit transfer vehicles and upper stages, mission planning, ground and flight operations, and support infrastructure, both on the ground and in orbit. The systems engineering approach ensures that the technologies developed — such as lightweight structures, long-life rocket engines, reliable crew escape, and robust thermal protection systems — will synergistically integrate into the optimum vehicle. To best direct technology development decisions, analytical models are employed to accurately predict the benefits of each technology toward potential space transportation architectures as well as the risks associated with each technology. Rigorous systems analysis provides the foundation for assessing progress toward safety and cost goals.

The systems engineering review process factors in comprehensive budget estimates, detailed project schedules, and business and performance plans, against the goals of safety, reliability, and cost, in addition to overall technical feasibility. This approach forms the basis for investment decisions in the 2nd Generation RLV Program's risk-reduction activities. Through this process, NASA will continually refine its specialized needs and identify where Defense and commercial requirements overlap those of civil missions.

1.0 Background

The U.S. Space Launch Initiative (SLI) is the central focus of the National Aeronautics and Space Administration's (NASA) Integrated Space Transportation Plan (ISTP), a comprehensive strategy for revolutionizing space transportation in the 21st century. The ISTP includes: (1) Space Shuttle Safety Upgrades, (2) near-term investments in 2nd Generation Reusable Launch Vehicles (RLV), and (3) long-term research for 3rd Generation RLVs and In-Space Transportation systems for future space exploration.

Building on 20 years of success with America's 1st Generation RLV—the Space Shuttle — the SLI defines the plan of action to design space transportation systems and develop advanced technologies for America's next-generation RLV. It addresses business risk reduction for 2nd Generation RLV development and technology risk reduction for NASA-unique systems (i.e., crew survival features), as well as enables potential Alternate Access to the International Space Station (ISS). Therefore, SLI is synonymous with the 2nd Generation RLV Program, which is managed by NASA's Marshall Space Flight Center (MSFC), with participation from NASA field Centers and aerospace contractors from coast to coast.

The 2nd Generation RLV Program's scope is not limited solely to the launch vehicle, but encompasses all elements of a space transportation system architecture, an integrated set of elements consisting of:

1. Earth-to-orbit launch vehicle
2. On-orbit transfer vehicles and upper stages
3. Mission planning
4. Ground and flight operations
5. Ground-based and on-orbit support infrastructure.

Figure 1 illustrates the interrelated nature of these elements, which function synergistically to accomplish the space transportation mission.

The 2nd Generation RLV Program is based on the philosophy that frequently launching NASA payloads on highly reliable reusable launch vehicles will significantly reduce the cost of space access, allowing the Agency to focus resources on its core missions of scientific discovery and exploration. [1] Overall goals are to substantially reduce technical and business risks associated with developing safe and reliable RLVs. NASA's specific goals are to:

- Improve safety — risk of crew loss — to less than 1-in-10,000 missions
- Decrease cost by a factor of 10 — to approximately \$1,000 per pound of payload launched to low-Earth orbit (LEO).

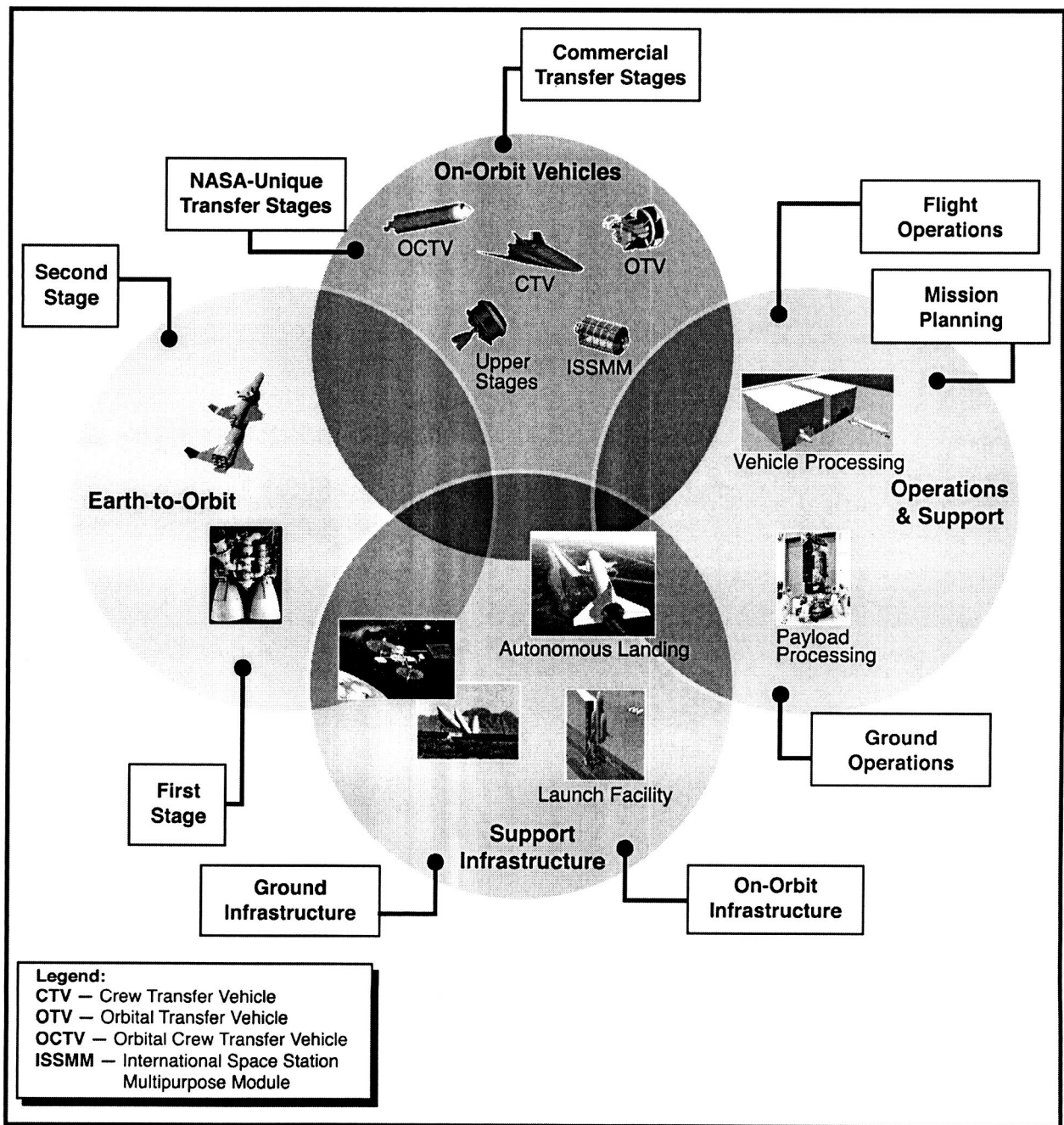


FIGURE 1. Space Transportation System elements.

Therefore, NASA is investing in strategic technology development in these areas for the express purpose of increasing safety and decreasing cost. While the space transportation architecture drives specific technology developmental objectives, the technologies ultimately enable the space transportation architecture. This cross-cutting character of space transportation technology development, viewed against a backdrop of multiple vehicle designs, is depicted in Figure 2.



FIGURE 2. Space Transportation System technology and design development.

The systems engineering and integration task consists of two distinct activities to be accomplished during the formulation phase covered by the 2nd Generation RLV Program:

1. Conduct System Studies — Define and comparatively evaluate candidate space transportation architectures, and develop and validate the associated systems requirements.
2. Coordinate Technology Developments — Maintain a technology portfolio to support evolving space transportation architecture(s).

Following is a description of the top-level systems engineering and integration processes developed to define a viable RLV architecture and mature the key technologies that will enable that architecture to meet Program objectives

2.0 Systems Engineering Process Overview

The overall systems engineering and integration process is illustrated in Figure 5. System definition begins with communication with customers and stakeholders. The Program solicits customer and stakeholder needs and wants, and provides space transportation system capabilities and costs as feedback. The systems definition activity quantifies customer needs and wants in terms of Level 1 Program Requirements and design reference missions (DRM), and quantifies system capabilities and costs in terms of mission-level figures of merit (FOM) — measures to which customers and stakeholders can relate. This activity also articulates the space transportation system's intended usage scenario in a Operations Concept Document for the architecture.

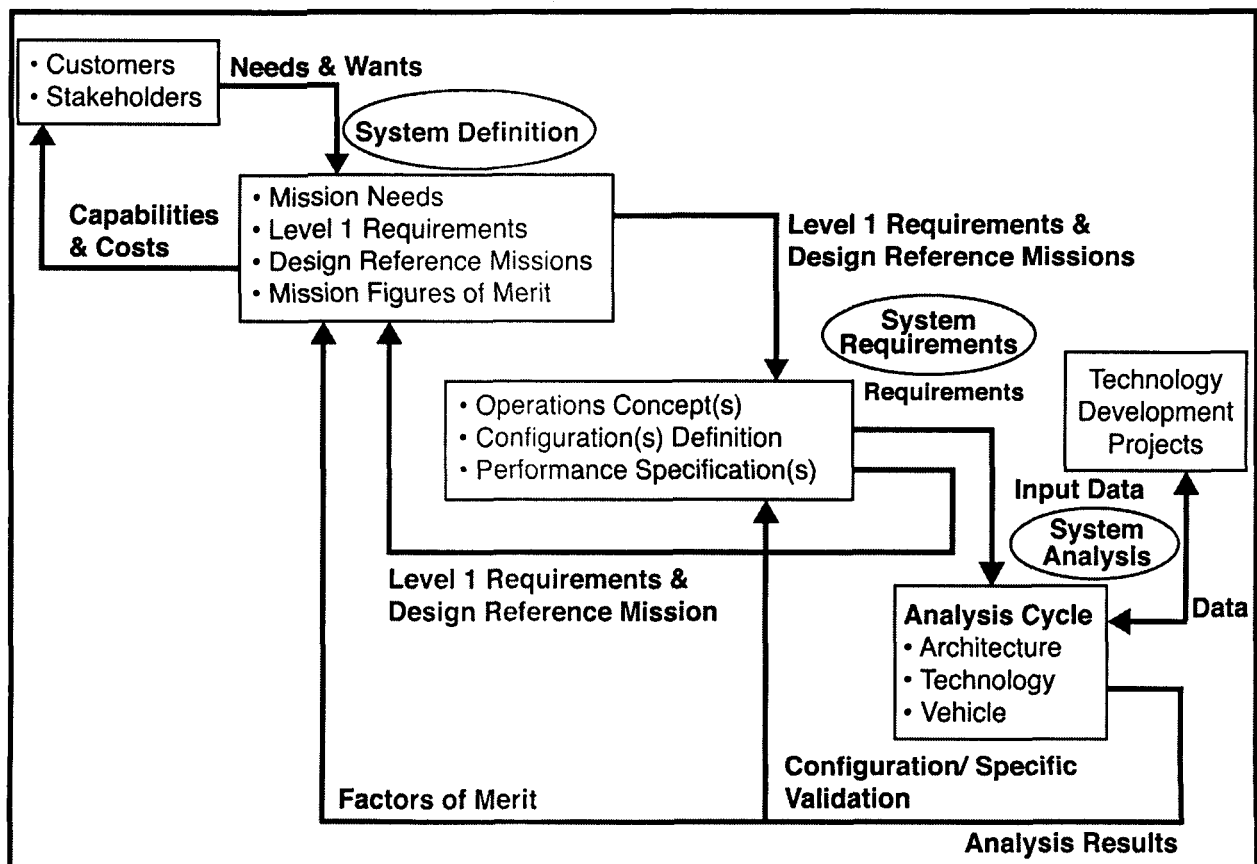


FIGURE 3. Systems engineering and integration process.

The systems requirements activity takes the system definition and develops a requirements allocation and flow-down for the space transportation system. This is the key integrating mechanism for the Program. It includes requirements synthesis with the individual projects within the advanced technology portfolio.

Given a requirements basis for a space transportation system, the systems analysis activity validates the requirements, using a design analysis cycle (DAC) process. The feedback provided indicates which requirements are valid and which are not; this information, in turn, influences the technology portfolio or may

even affect Level 1 Requirements. The output of a design analysis cycle will also include the mission-level figures of merit in support of the system definition activity. Over time, successive cycles will result in convergence to the optimal space transportation system architecture, as illustrated in Figure 6.

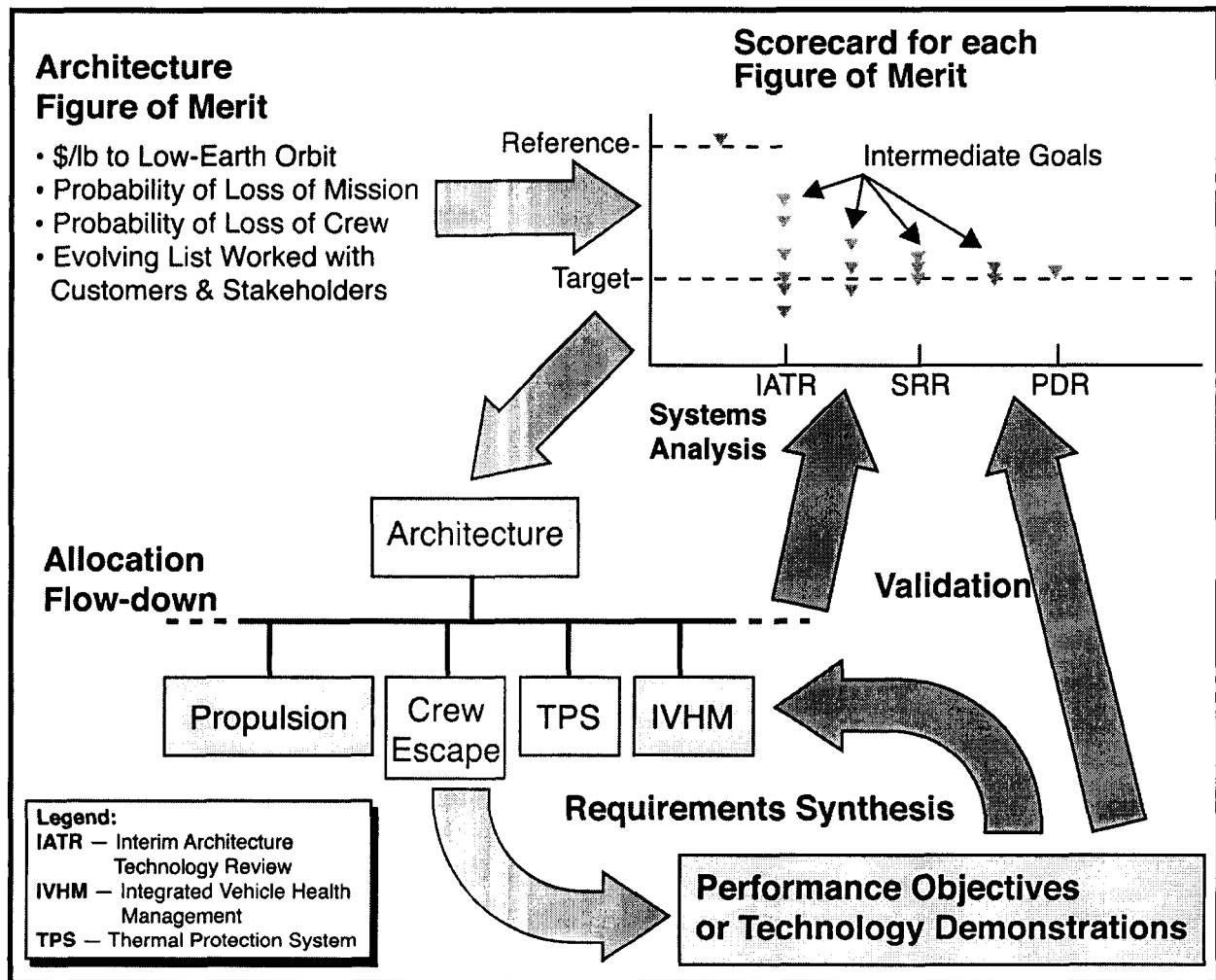


FIGURE 4. Convergence to the optimal Space Transportation System architecture.

3.0 Technology Integration

The space transportation architecture will achieve the goals of increased safety and reduced costs only through advancements in the state-of-the-art in several key technology areas. These key technologies include:

- propulsion and upper stages,
- thermal protection systems (TPS), airframes, and large cryogenic tanks
- avionics and vehicle subsystems,

- crew escape and survival,
- flight mechanics,
- integrated vehicle health management (IVHM), and
- operations. [2]

The progress in maturing the respective technologies is determined through periodic assessment of the technological readiness at various stages with a numerical grade. A numerical value of 1 signifies the starting of the program and a value of 9 represents full technological readiness, indicating 100% confidence in the mission performance of a technology. An exit criteria can be set at some value between 1 and 9 that corresponds to design readiness – that is, the technology, while not yet fully proven, is mature enough to include in the system design with an acceptable degree of risk. The following technology readiness criteria provide a numerical grade by way of requirements to be met at each level of technology maturation are defined below **Reference DAU Systems Engineering Fundamentals**:

1. Basic principles observed and reported
2. Technology concept and /or application formulated (candidate selected)
3. Analytical & experimental critical function, or characteristic proof-of-concept, or completed design
4. Component and/or breadboard test in a laboratory environment
5. Component (or breadboard) verification in a relevant environment
6. System/Subsystem (configuration) model or prototype demonstrated and/or validation in a relevant environment
7. System prototype demonstrated in flight
8. Actual system completed and “flight qualified” through test and demonstration
9. Actual system “flight proven” on operational flight

The following sections discuss the establishment of target performance requirements for technologies, the monitoring of progress in achieving technology requirements, and the overall systems analysis process which assess the technology risk and payoff within the context of the evolving space transportation architecture.

3.1 Technology Requirements Development

A Systems Requirements Document (SRD) will be developed to describe an architecture's technical, operational, and support requirements, and the allocation of the system requirements to the five architectural elements (see Section 1.0), as well as to define the interfaces between the architectural elements. Inextricably coupled, the 2nd Generation RLV Level 1 Program Requirements document serves as the “parent” document for the SRD, whose content can be traced directly to Level 1 Requirements. For example, Level 1

Requirements include a probability of no greater than 1 in 10,000 for loss of crew in a mission. The SRD will transform this probability into reliability and redundancy requirements at the system level, which will subsequently be allocated to the elements of the architecture. In this way, the requirements for individual system components can be derived by successively refining the requirements to lower and lower levels of detail.

As previously discussed, the Program includes various technology development projects. NASA's success in advancing the state of the art in these key technologies as it pertains to safety and cost effectiveness will enable those goals. Conversely, the extent to which the state of the art can be advanced in these technologies will also constrain the candidate system architectures. For instance, if an engine cannot be developed that is sufficiently safe and economical, the Program will not meet its safety and cost goals. However, the definition of "sufficient" safety and economic needs for engines varies between candidate architectures. Hence, while the architectures *drive* the technologies, the technologies *constrain* the architectures.

A requirements synthesis process has been developed to both assure that technology development is responsive to the needs of the candidate architectures and to mutually assure that the architectures are based on technologies that can be realized. The relationship between SRD development and technology development requirements is illustrated in Figure 11. The requirements synthesis process, illustrated in Figure 12, begins with the technology project's identification of key technical parameters.

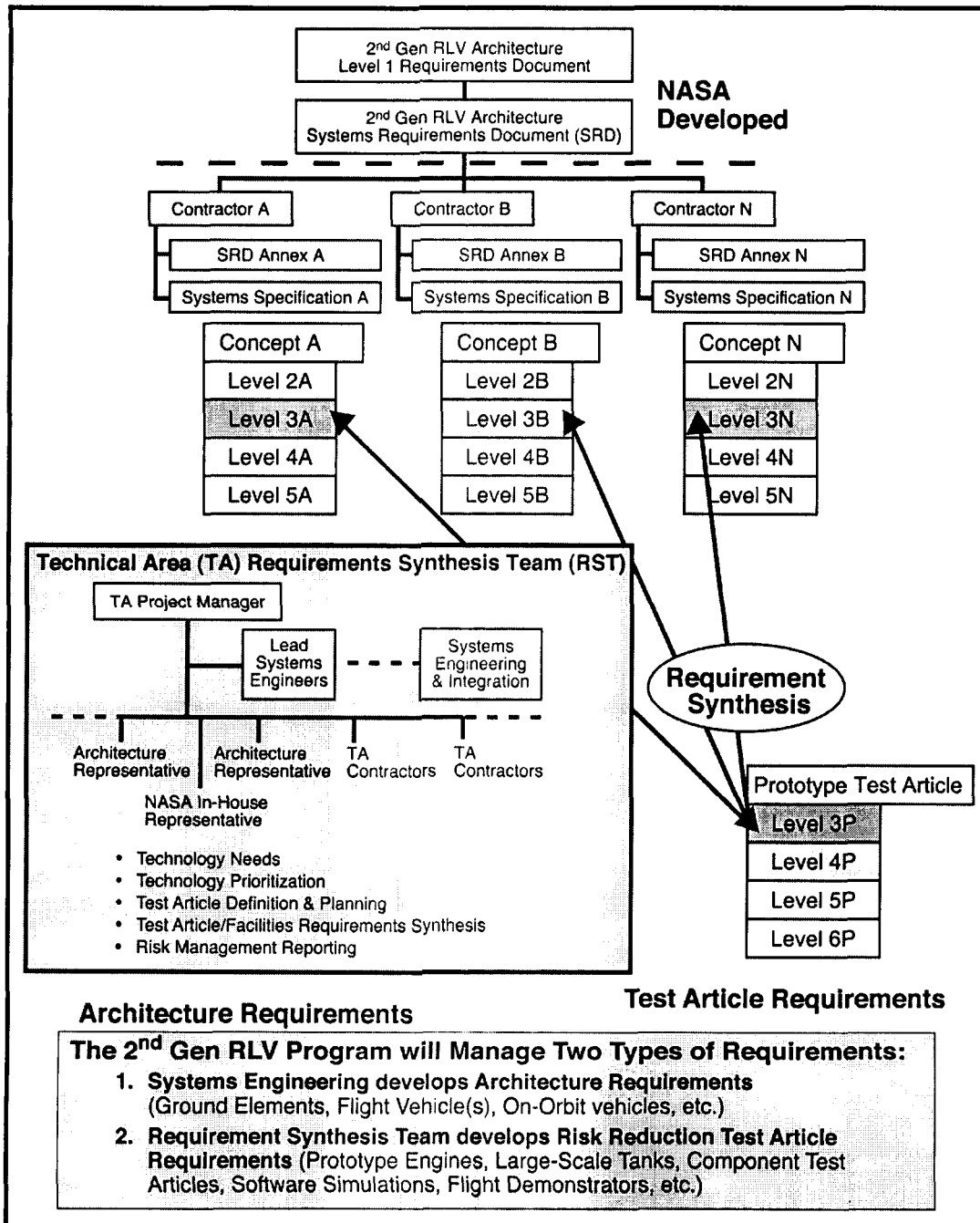


FIGURE 5. Relationship between Systems Requirements Document development and technology development requirements.

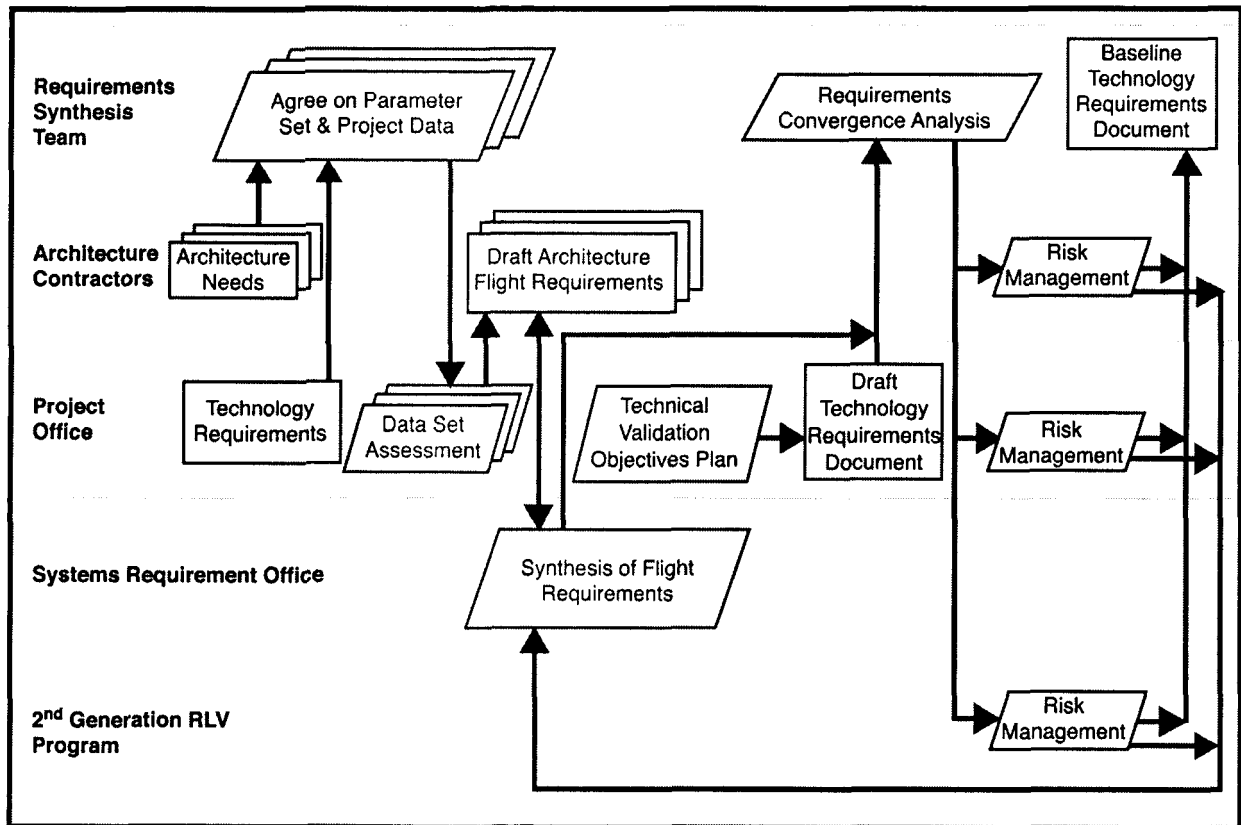


Figure 6. Requirements synthesis process.

Data for the technical parameters are then collected for the various candidate architectures and synthesized into a single set that spans, as much as possible, the candidate architectures. A convergence analysis of these synthesized architecture requirements against the technology project's requirements identifies areas of divergence between the architectural needs and the planned technology developments. These divergences are then managed as Program risks, and are either accepted as a risk or mitigated in some manner, such as changing the technology project's scope or imposing a constraint on the system architectures.

The requirements synthesis process is iterative, with the cycle driven by key Program and project milestones, such as design reviews. This process: (1) assures that the systems requirements are feasible, with a known level of technical risk, and (2) provides technology development project objectives and priorities.

3.2 Technology Performance Measurement

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3.2 Technology Performance Measurements (TPMs)

The TPM is a methodology that charts the history of the values of a selected set of requirements quantifiable in time for the purpose of clearly illustrating the changes in value in relation to Program/Project events and goals for that requirement value. A set of Technology Performance Measurements (TPMs) for each of the 2nd Generation Reusable Launch Vehicle (RLV) program technology tasks are being developed, baselined and maintained by Systems Engineering.

Each Technology Project provides monthly inputs for architecture contractor-identified TPMs that are applicable to their proposed concepts and within scope of the technology task. To assess the technology risk, a unique TPM chart will be used to track historical values and clearly illustrate progress against assigned threshold and objective values. Also, the TPMs will have traceability to the Technology Project requirements, which will be maintained in a Systems Engineering requirements database. The TPMs provide technology health status data, architecture relevancy & integration data, and an application for cost and risk mitigation information for Program goals and objectives.

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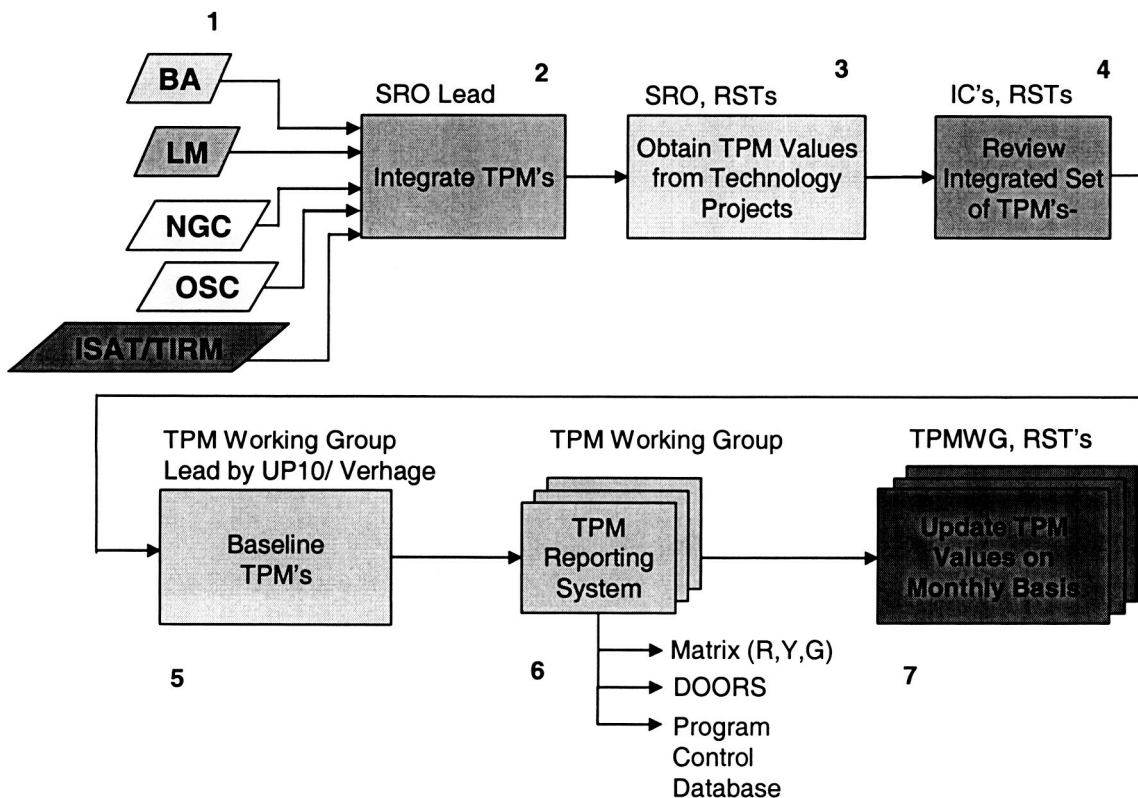


Figure 7. Technology Performance Measurements (TPMs) Process.

3.3 Systems Analysis

Rigorous system analysis will indicate whether a system configuration, such as a candidate 2nd Generation RLV architecture, will satisfy requirements. The systems analysis process addresses five criteria, as shown in Figure 13:

1. Technical Viability
2. Technology Risk
3. Design Reference Missions
4. Safety/Reliability
5. Cost/Economics.

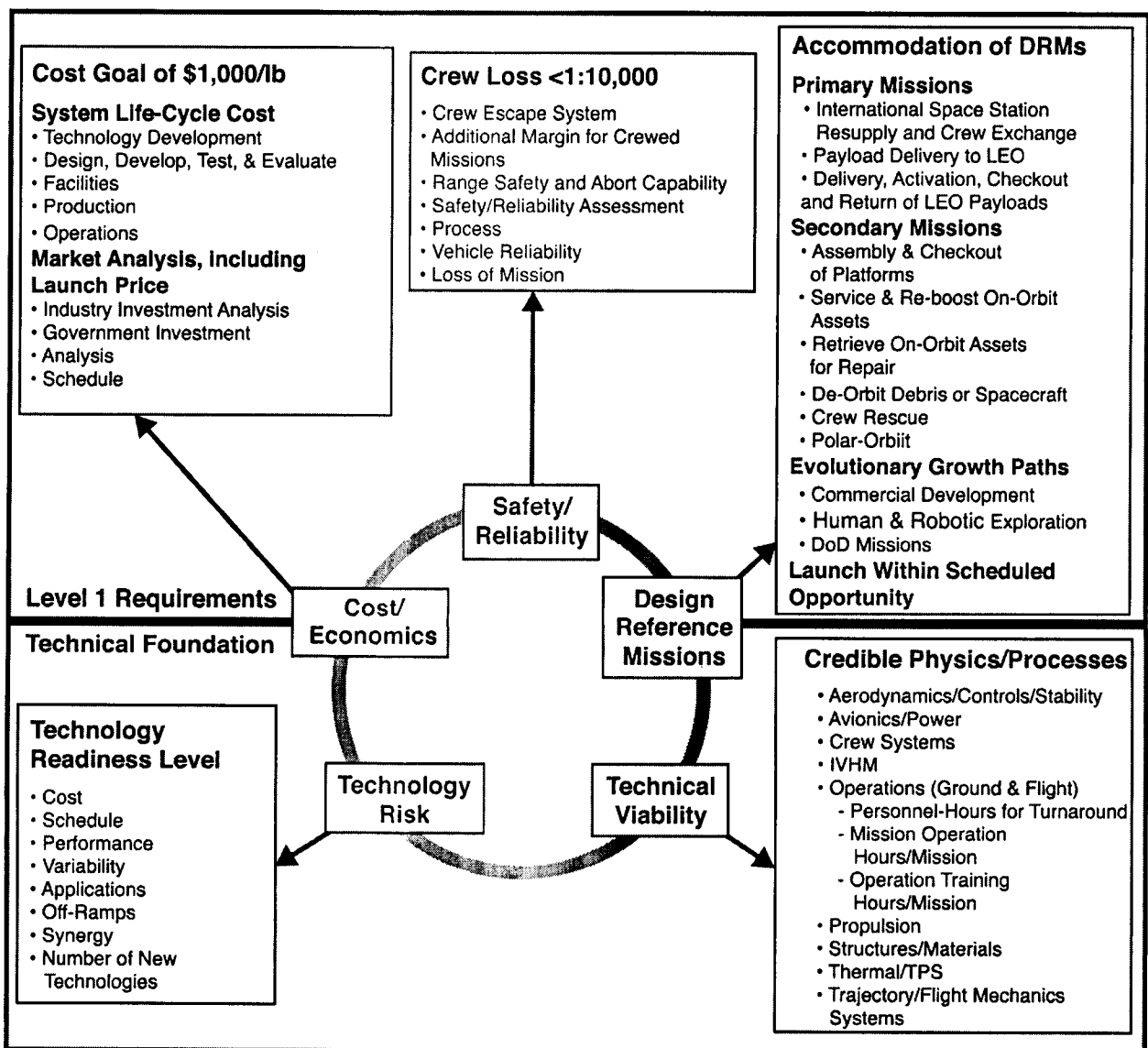


FIGURE 7. Criteria addressed by the systems analysis process.

Obviously, the first step in an architecture systems analysis is to model the system and determine whether it is credible from a physical science viewpoint. This series of analyses will answer rudimentary questions such as "Can it reach orbit?" and "Will it survive the natural environment?"

Given that the configuration possesses credible physics and processes, systems analyses then focus on the technology readiness levels (TRL) of the various architecture elements. This series of analyses answers questions such as "Will the technology be ready in time?" and "What is the impact if the technology does not achieve performance goals?" The risk reduction technology projects and the mission requirements synthesis process provide data to reduce uncertainty in these analyses.

Given a candidate architecture that possesses credible physics/processes and realistic technology assumptions, the next set of analyses address the system's functionality across the spread of operational scenarios characterized by the design reference missions. The safety/reliability and cost/economics associated with operating the system will also be modeled and analyzed to answer the questions "How safe is it?" and "How much will it cost to acquire and operate?" The parameters included in the systems analysis process are depicted in Figure 13. Note also that the mission-level FOMs discussed in Section 2.1 are a subset of the systems analysis parameter set.

Repeating the systems analysis process for a large number of candidate architectures will validate the systems requirements. For example, if multiple architectures meet the 1-in-10,000 loss of crew requirement, it may be assumed this is a valid requirement that can be met by the 2nd Generation RLV when it is developed and operational. Conversely, if a requirement cannot be validated in that no candidate system architectures meet the requirement, the systems analysis process provides for requirements "push-back" to establish a valid requirement. Because the requirements are allocated across multiple architectural elements and based on assumed performance of various technologies, requirements "push-back" will lead to a requirement reallocation or relaxation for the architectural elements and/or the technologies, which prompts a new analysis.

One iteration of the systems analysis process is called a design analysis cycle. Over time, the character of DACs will evolve, growing in fidelity and precision; as it becomes available, test data resulting from risk reduction technology projects will be included in the DACs. In the near term, DACs will focus on the evaluation of a large number of candidate system architectures (refer to Figure 4). Subsequently, the DACs' focus will shift toward greater detail on a smaller number of candidate architectures. Accordingly, the systems requirements validation will approach completion and the validation focus will shift to lower-tier requirements associated with architectural elements, subsystems, and

components. Likewise, the mission-level FOMs will begin to stabilize and generally exhibit reduced variability over time. In this way, the systems analysis process: (1) validates systems requirements, and (2) determines the relative merit of various candidate systems architectures and technologies.

4.0 Summary **to be written as narrative**

- Provided overview of SLI, setting context for approach
- Reviewed technology drivers
- Discussed overall SE&I approach
- Discussed technology readiness levels, requirements development & synthesis, technology performance measurement, and systems analysis
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5.0 References **to be added**